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Optimal Operation of Electronically-Coupled MicroGrids

التشغيل الأمثل للشبكات الكهربية الصغيرة المرتبطة إلكترونياً

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ملخص البحث:

الشبكات الصغيرة هى منظومة توليد وتوزيع للقوى الكهربية بحيث تكون المولدات الكهربية على مقربة من المستهلكين. وعادة ما تكون هذه المولدات محدودة القدرة ويتم ربطها معا لتغذية الأحمال فى منطقة صغيرة. ويمكن أن تعمل الشبكات الصغيرة مرتبطة مع شبكة الكهرباء الرئيسية أو أن تعمل بشكل مستقل عنها (كجزيرة مستقلة)، ويؤدى ربط كميات كبيرة من الطاقة الغير تقليدية مع شبكة التوزيع إلى مشاكل في الشبكة حيث أنها مصممة للعمل فى ظروف التشغيل التقليدية، ومن الممكن حل هذه المشكلة من خلال استخدام إلكترونيات القوى.

ويقدم هذا البحث صيغة عامة لتحديد استراتيجية التشغيل الأمثل بتكلفة اقتصادية لشبكة صغيرة مرتبطة الكترونيا. والهدف الرئيسي هو تقليل تكلفة التشغيل الإجمالية مع اعتبار قيود كل من المنظومة الكهربية ومنظومة الربط باستخدام ألكترونيات القوى وذلك فى كل من حالتى التشغيل للشبكة الصغيرة، ويقدم البحث أيضا نمذجة لمنظومة عواكس من إلكترونيات القوى لربط وحدات التوليد الموزع بشبكة الكهرباء الرئيسية باستخدام هذا النماذج و حل مشكلة تدفق القدرة بطريقة نيوتن رافسن، ومن أهم سمات المنهجية المقترحة هو أنها تقدم حلا للمشكلة بناءً على المتغيرات الداخلية لكل وحدة توليد موزع. وقد تم تطوير برنامج كمبيوتر فى بيئة الماتلاب لتمثيل المنهجية المقترحة وقد تم اختبار هذا البرنامج فى حالات تشغيل مختلفة وتم تطبيقه على شبكة صغيرة مكونة من ثلاث وحدات توليد منها اثنان مرتبطتان بالشبكة من خلال أنواع مختلفة من العواكس وتم التحقق من صحة البرنامج فى كل من حالتى التشغيل لهذه الشبكة.

Abstract

MicroGrids are power generation and distribution systems in which users and generators are in close proximity. They usually have limited power generation capacity, and are networked together to meet a small area's load demand. MicroGrid, (MG) can operate interconnected to the main power network or be operated autonomously, if they are isolated from the power grid (islanded mode). The interconnection of large amounts of nontraditional generation causes problems in a network designed for conventional operation. The use of power electronics interfaces offers a potential solution.

This paper presents a generalized formulation to determine the optimal operating strategy and cost optimization scheme for an electronically–coupled MicroGrid. The major objective is to minimize the overall operating cost considering both the power system and power electronics constraints in the two modes of the MG operation. The paper also presents steady-state, fundamental-frequency models of power electronic converters systems for coupling distributed generation (DG) units to the utility power grid based on Newton–Raphson and the developed models. A feature of the proposed approach is that it solves for the internal variables of each DG unit. A Matlab program is developed to represent the proposed algorithm. The program is tested in various network conditions and verified by applying it to a MG with three DG units from which two units are electronically-coupled to the grid in the two modes of operations.

Keywords: ***MicroGrid, distributed generation, optimal operation, power flow, Power electronics, Converters***

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1. Introduction

MicroGrids are defined as low-voltage networks with micro-generation sources (PV, micro turbines, fuel-cells, micro-wind generators); together with local storage devices and controllable loads (e.g. water heaters and air conditioning). The unique feature of MicroGrids is that, although they operate mostly connected to the distribution network, they can be automatically transferred to islanded mode in case of faults in the upstream network and can be resynchronize after restoration of the upstream network voltage [1].

From the customer point of view, MGs provide both thermal and electrical needs and in addition enhance local reliability, reduce emissions, improve power quality by supporting voltage and reduce voltage dips and potentially reduce costs of energy supply. From the utility point of view, application of distributed energy sources can potentially reduce the demand for distribution and transmission facilities [2]. Clearly, distributed generation located close to loads will reduce flows in transmission and distribution circuits with two important effects: loss reduction and ability to potentially substitute for network asset. Figure 1 shows a schematic diagram of MicroGrid architecture.

Due to the speed response and flexibility of renewable sources, power-electronic converter systems of electronically-coupled DG units are the prime candidates to perform the required control and/or protection functions to meet the MG objectives [3]. The main types of converters used for DG units are [4]:

- AC/DC/AC PWM converter which illustrates the use of universal bridge, multi meter, and powerful blocks, as well as discrete control blocks of the extras library. A conventional AC–DC–AC conversion is controlled by back-to-back connection of current or voltage DC link PWM converter systems.
- AC/AC converters which are used to change either the voltage level or the frequency (international power adapters, light dimmer). In power distribution networks AC/AC converters may be used to exchange power between utility frequency 50 Hz and 60 Hz power grids. AC/AC converters can be categorized into [5]:
    - o Converters with a DC-link.
    - o Cycloconverter.
    - o Hybrid Matrix Converters.
    - o Matrix Converters.

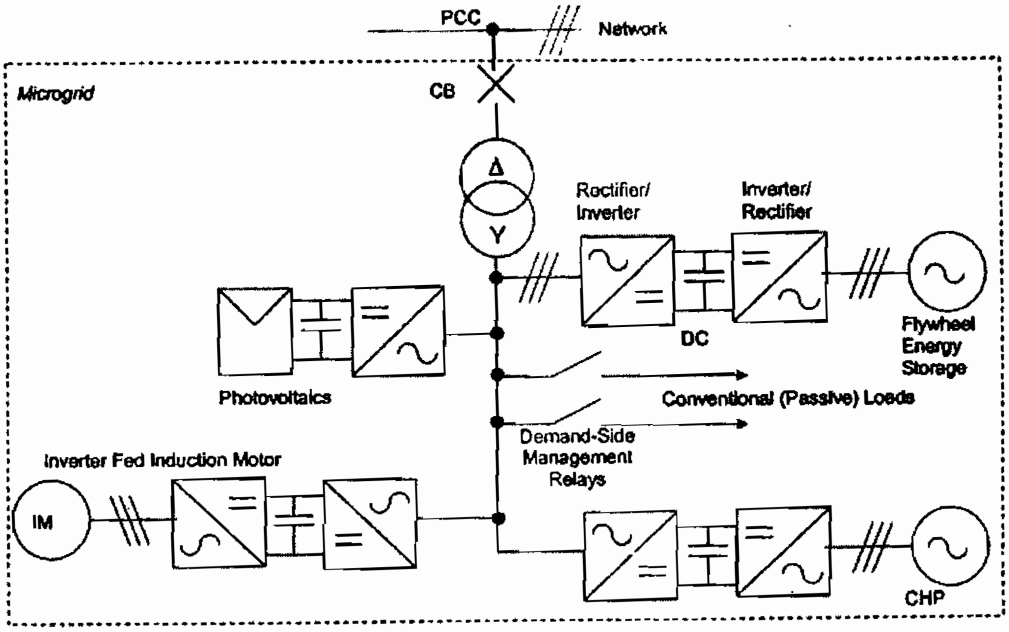

Fig.1. MicroGrid Architecture

In order to achieve higher power density and reliability, it makes sense to consider matrix converters that can directly convert an AC power supply of variable voltage and frequency into an ac voltage of fixed amplitude and frequency. Matrix converter is a single stage converter. All the reasons lead to the development of matrix converter. Several publications on matrix converters have dealt with the modulation strategies to improve the performance of the matrix converter .The constraints of these converters are the modulation index (MI). Variation of modulation index can change the total harmonic distortion. Large values of MI in sinusoidal PWM techniques lead to full over modulation [6].

Active/reactive power dispatch problems have been the research subject of power system community since the early 1960's. The problem is usually formulated as an optimal power flow (OPF) problem. The OPF problem [7] is an important class of problems in the power industry. A Newton-based OPF is developed for implementation into a power system simulation environment. The OPF performs all system control while maintaining system security. System controls include generator megawatt outputs, transformer taps, and transformer phase shifts, while maintenance of system security ensures that no power system component's limits are not violated.

This paper presents a generalized formulation to determine the optimal operating strategy and cost optimization scheme for an electronically- coupled MicroGrid. The major objective is to minimize the overall operating cost considering both the power system and power electronics constraints in the two modes of the MG operation. The main contribution of this study is to make sure that the converter constraints are satisfied for both types used (AC/DC/AC converter and AC/AC matrix converter).

2. Problem Formulation

The problem is to determine generator power set points so that the overall cost of power generation is minimized, while respecting limits on the generator's capacity, transmission power flow constraints, and the power electronic constraints.

To optimize the operation of electronically coupled MG, fuel cost is chosen to be minimized as generally used in economic dispatch problem. But in MG as a special case, two different sets of constraints have to be considered namely; power flow constraints and power electronic constraints.

In this study, two types of converters are used; three phase matrix converter and AC/DC/AC converter.

The general mathematical formulation of MG optimal power flow is as follow [7]:

$$Min\{F(P_g) = \sum_{i=1}^{n_g}(a_i P_{gi}^2 + b_i P_{gi} + c_i)\} \quad (1)$$

Where n_g is the number of generation including the slack bus and P_{gi} is the generated active power at bus i. The cost parameters for i^{th} generator are: a_i, b_i and c_i

Power flow constraints include bus voltage limit, active and reactive generation limit, and thermal limit (line flow limit):

i. Bus voltage tolerance limit:

$$V_{i\min} \le V_i \le V_{i\max} \quad (2)$$

ii. Active and reactive power generation limits:

$$P_{i\min} \le P_i \le P_{i\max} \quad (3)$$

$$Q_{i\min} \le Q_i \le Q_{i\max} \quad (4)$$

iii. Line flow limits

$$S_{ij} \le S_{ij\,max} \quad (5)$$

Power electronics constraints include constraints for the converter modulation index for both types used in this work as follow:

iv. The AC/DC/AC converter constraints are as follows [8]:

- Converter magnitude modulation index $A_{mi2} \le 1$ (6)
- Converter Angle modulation index $0 \ge \alpha_{mi2} \ge -90°$ (7)

v. The matrix converter constraints [6]:

- Converter magnitude modulation index $A_{m3} \leq 0.866$ (8)
- Converter angle modulation index

$$90^{\circ} \geq \alpha_{m3} \geq 0 \tag{9}$$

The steady state real and reactive power components at the bus and the generator terminals are proportional to the component of currents [9].

$$P = V_m I_d \tag{10}$$

$$Q = V_m I_q \tag{11}$$

$$P_g = V_{mg} I_{dg} \tag{12}$$

$$Q_g = V_{mg} I_{qg} \tag{13}$$

$$P_g = P + R_f\left(I_d^2 + I_q^2\right) + R_g\left(I_{dg}^2 + I_{qg}^2\right) \tag{14}$$

2.1. The Settings of the AC/DC/AC Converter System are as follows:

The amplitude and angle modulation indices of inverter can be expressed as [9]:

$$\mathrm{A}_{\mathrm{mi2}} = \frac{2}{V_{dc}} \sqrt{A_{x1} + A_{x2}} \tag{15}$$

Where:

$$A_{x1} = \left(L_g w_g I_{dg} + R_g I_{gq}\right)^2$$

$$A_{x2} = \left(-V_{mg} - L_g w_g I_{qg} + R_g I_{dq}\right)^2$$

$$\alpha_{mi2} = \theta_g + \tan^{-1}\left(\frac{(L_g I_{dg} + R_g I_{gq})}{(-V_{mg} - L_g w_g I_{qg} + R_g I_{dq})}\right) \tag{16}$$

The amplitude and angle modulation indices of rectifier are expressed as:

$$\mathrm{A}_{\mathrm{mo2}} = \frac{2}{V_{dc}} \sqrt{A_{y1} + A_{y2}} \tag{17}$$

where:

$$A_{y1} = \left(l_f \mathrm{w} I_d + R_f I_q\right)^2$$

$$A_{y2} = \left(V_m + l_f \mathrm{w} I_q - R_f I_d\right)^2$$

$$\alpha_{mo2} = \theta + \tan^{-1}\left(\frac{(l_f \mathrm{w} I_d + R_f I_q)}{V_m + (l_f \mathrm{w} I_q - R_f I_d)}\right) \tag{18}$$

2.2. The Setting of the Matrix Converter

For this converter type the amplitude and angle modulation indices are expressed as [9]:

$$\mathrm{A}_{\mathrm{m3}} = 0.827 \left(\frac{V_o}{V_i}\right) = 0.827 \left(\frac{\sqrt{V_{do}^2 + V_{qo}^2}}{\sqrt{V_{di}^2 + V_{qi}^2}}\right) \tag{19}$$

$$\alpha_{m3} = \alpha_i + \alpha_o$$

$$\alpha_{m3} = tan^{-1}\left(\frac{V_{qi}}{V_{di}}\right) + \theta_g \, tan^{-1}\left(\frac{V_{qi}}{V_{di}}\right) + \theta \tag{20}$$

The factor 0.827 in (19) indicates the maximum value of $\mathrm{A_m}$ for one per unit of voltage at the converter input–output terminal [9].

Generally, the optimal operating point from the optimal power flow satisfies the power flow constraints. However, the power electronic constraints have to be checked separately. If this optimal point violates the power electronic constraints, this point has to be changed to satisfy those constraints. The new operating point will scarify more fuel cost, but this should happen making sure both power and power electronic constraints are satisfied.

3. Proposed Algorithm

The proposed approach represents the power electronic interface and the prime source of the DG units based on a *dqo* frame in MG power flow analysis program [9]. Thus, it ensures that the power flow solution meets the requirements and constraints of not only the AC network of the MG but also those of the converters and prime sources of the DG units. The proposed algorithm includes three main steps. Step 1, based on the Newton-Raphson OPF algorithm that solves for the AC network of MG. Step 2 utilizes the calculated electrical parameters at the Point of Common Coupling (PCC) of each DG unit to solve for the internal variables of DG units while satisfying the power electronics constraints of both types of converters. While, step 3 checks the power electronic constraints and forces the system to satisfy them even by scarifying some of the fuel cost.

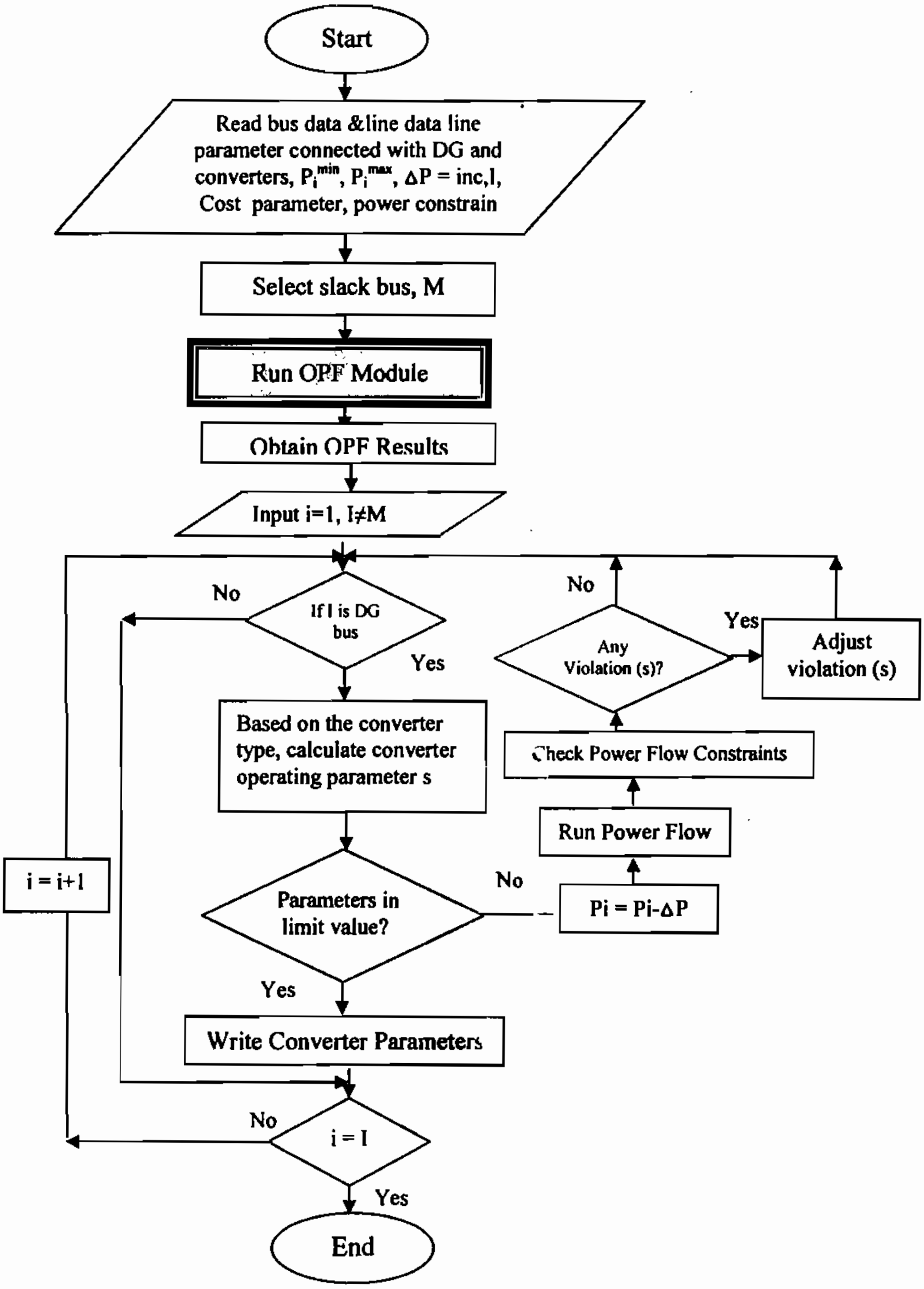

Figure 2: Flowchart of the Proposed Optimal Operation of the Electronically Coupled MG

The proposed algorithm started by defining the slack bus and entering the input data:

1. Power system data: voltage and angle at slack bus, the active and reactive power components at load (PQ) buses and the active power components and voltages at generator (PV) buses, line data, voltage limits, generation limits, line flow limits, and network frequency.

2. DG unit's data: Generator internal voltage, voltage angle, generators reactive power components, generator resistance and reactance.
3. Converters parameters and converter DC link voltage.

After entering the data, OPF of the MG is performed to obtain the optimal operating parameters of the MG. These parameters include: real and reactive power components at the slack bus, reactive power component, voltage angle at the generator (PV) bus and the voltage amplitude and voltage angle at the load (PQ) bus. Then, the operating parameter of the DG units and the setting of converters are calculated. If all the calculated variables are within limited values the OPF analysis is complete and the obtained values are the final ones. On other hands, if any variable of anyone of the electronically-coupled DG unit violates its limit, the program will change the real power value, and then step 3 and Step 2 are repeated until the limit condition is satisfied. Fig (2) shows the flow chart of the proposed algorithm.

4. Numerical Application

4.1. System Description

A Matlab program is developed to represent the proposed algorithm. The program is tested in various network conditions and verified by study cases. The cases are based on the LV case network shown in Fig. 3 as the main testing network. This MG model was developed in [9]. The tested MG composed of three PV buses and two load buses (PQ buses). One of the three DGs is considered as a conventional synchronous generator unit (Slack bus), that represents either a gas-fired or a diesel-generator unit. DG2 is interfaced to bus2 through an AC/DC/AC converter system which is composed of two back-to-back connected VSCs. DG3 (bus3) utilizes a direct AC/AC matrix converter as the interface medium. DG2 and DG3 are assumed as electronically-coupled mini-and micro-turbine generator units.

The bus and line data of the system are indicated in the Tables 1 and 2. In case that MG operates at autonomous mode bus 6 is inactive, whereas in the other mode (grid connected mode) it is considered as the slack bus. The maximum and minimum limits on active, reactive power and voltage limits and the cost parameters of the source are listed in Table 3 and 4 [10].

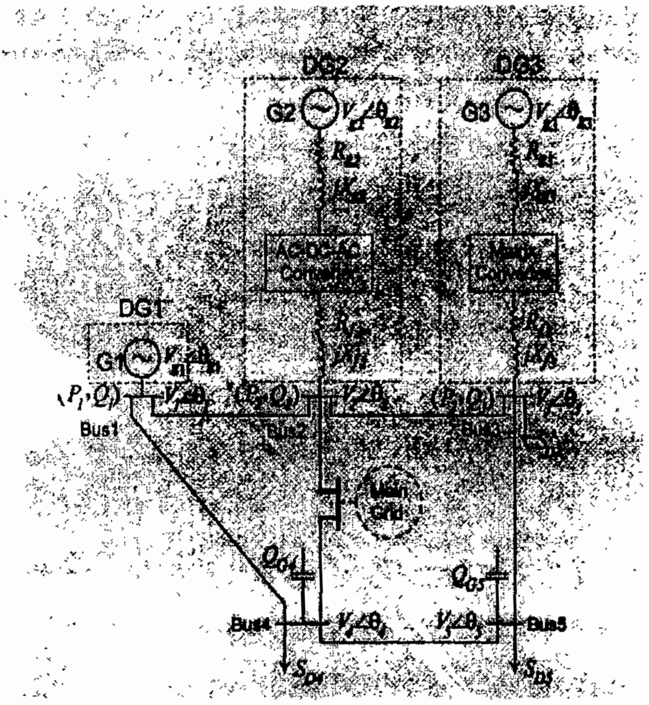

Fig. 3: Studied MicroGrid System with Three DG Units

Table1: Bus Data of the MicroGrid

Bus No.	Bus Type	P_G MW	Q_G MVar	P MW	Q MVar	V pu
1	Slack bus*	50	0	0	0	1
2	PV	100	0	0	0	1
3	PV	100	0	50	10	1
4	PQ	0	0	150	-55	1
5	PQ	0	0	125	-85	1
6	Slack bus **	200	0	0	0	1

*for autonomous mode

** for grid connected mode

Table 2: Line Data of the MicroGrid

line	R pu	X pu	0.5 (B) pu	S_{max} MVA
1-2	0.00050	0.0036	0.0207	250
1-4	0.00470	0.02375	0.0724	250
2-3	0.00245	0.0100	0.1026	150
2-6	0.00067	0.0050	0.0288	300
2-4	0.00135	0.0103	0.0576	300
3-5	0.00140	0.0103	0.0594	150
4-5	0.00035	0.0025	0.0144	250
4-6	0.00175	0.0050	0.0288	350

Table 3: Active, Reactive, and Voltage Limits of the MG Sources

Bus no.	P_{min}	P_{max}	Q_{min}	Q_{max}	V_{min}	V_{max}
1	10	250	-300	300	0.9	1.00
2	10	300	-300	300	0.9	1.00
3	10	270	-300	300	0.9	1.00
6	10	250	-300	300	0.9	1.00

Table 4: Cost Parameters of the MG Sources

Bus no.	a $/MW²/.hr	b $/MW.hr	c $/hr
1	0.11	5	150
2	0.085	1.2	600
3	0.1225	1	335
6	0.28	10	150

4.2. Optimal Operation Problem

The objective of the optimal power flow is to minimize the generation cost and keep the power outputs of generators, bus voltages, shunt capacitors/reactors and transformers tap-setting in their secure limits. The objective function for the entire power system can then be written as the sum of the quadratic cost model at each generator. The main contribution of this study is to make sure that the converter constraints are satisfied for both types used (AC/DC/AC converter and AC/AC matrix converter). So, the developed program, in a second step, solves for the internal parameters of the DR units with the coupling converter. The whole program represents optimal operation of the MG in both modes of operation (autonomous and non-autonomous) considering the power electronic constraints.

4.2.1. Optimal Operation of MG in Autonomous (Isolated) Mode

Running the proposed algorithm, for the MG system shown in Fig 3 with the data listed in Tables 3 and 4 in the autonomous mode. The output of the OPF module is shown in Table 6 and Table 7.Table 6 gives bus result and Table 7 gives the flow in lines.

Table 6: Bus Result for MG System in Autonomous Mode after OPF

Bus no	V pu	Θ deg	P_G MW	Q_G MVar	P_L MW	Q_L MVar
1	0.996	0.0	89.82	-25.42	0	0
2	0.995	-0.061	138.66	-84.80	0	0
3	0.994	-0.405	97.22	-78.04	50	10
4	1.00	-0.882	0	0	150	-55
5	1.00	-0.949	0	0	125	-85
Total			325.71	-188.25	325	-130
Objective value = 5477.37 $/hr						

As shown from Table 6, all buses voltage are within the specified limit (± 5%) of the rated value. It also shows that the active power from different generators are optimized with objective function of 5477.37 $/hr. And all lines flow apparent power are within limits as shown in Table7.

Table 7: Results of flow in lines for MG System in Autonomous Mode after OPF

Line #	To Bus #	From Bus #	Line Flow, MVA	Max Flow, MVA
1	1	2	31.998	250
2	1	4	68.467	250
3	2	3	35.636	150
4	2	4	149.92	300
5	3	5	111.373	150
6	4	5	48.92	250

In this case the modulation amplitude of the AC/DC/AC converter at DG2 (A_mi2 = 1.3622) violates its limit value (1.0). So, the operating point has to be changed to satisfy this constraint by applying step 3.

After, performing this step, the final output of the PF module is shown in Table 8 and Table 9. The first table gives bus result whereas the second one gives the flow in lines.

Table 8: Bus Result for MG System in Autonomous Mode after PF

Bus no	V pu	Θ deg	P_G MW	Q_G MVar	P_L MW	Q_L MVar
1	1.00	0.00	210.5	-66.53	0	0
2	1.00	-0.292	18.66	-48.45	0	0
3	1.00	-0.615	97.22	-61.12	50	10
4	1.005	-1.059	0.00	0.00	150	-55
5	1.006	-1.131	0.00	0.00	125	-85
Total			326.4	-176.1	325	-130
Objective value = 8321.247 \$/hr						

Table 9: Results of flow in lines for MG System in Autonomous Mode after PF

Line #	To Bus #	From Bus #	Line Flow, MVA	Max Flow, MVA
1	1	2	140.642	250
2	1	4	82.616	250
3	2	3	35.257	150
4	2	4	149.341	300
5	3	5	106.002	150
6	4	5	57.099	250

However the objective value changes from 5477.37 $/hr to 8321.247 $/hr. Table 10 illustrates the converter parameters of MG system in autonomous mode after using the OPF and PF steps.

Table 10: Converter Parameters of MG System in Autonomous Mode

Setting	After Opf	After Pf
	Value (PU)	Value (PU)
A_{mi2}	1.3622	0.9505
A_{mo2}	0.7884	0.8256
α_{mi2}	30.9745	30.1939
α_{mo2}	-5.3964	-1.1892
A_{m3}	0.3444	0.4327
α_{m3}	13.8911	9.2482

4.2.2. Optimal Operation of the MG system in grid-connected mode

The proposed algorithm is applied to the test system in grid-connected mode by connecting the main grid to bus 6 and considering it as the slack bus.

From Table 11, the objective value is 5451.30 $/hr, which is slightly lower than the case of the isolated mode. Also, all bus voltage are within the limit. However, the voltage of bus 5 is in the limit as it has a very high capacitive load. Table 12 gives the flow in lines when MG connected with the main grid. As shown from Table 12, all line flows are in the permissible limits.

In this case the modulation amplitude of the AC/DC/AC converter at DG2 (A_mi2 = 1.338) violates its limit value (1.0). So, the operating point has to be changed to satisfy this constraint using step 3. After, performing this step, the final output of the PF module is shown in Table 13 and Table 14, for bus result and flow in lines, respectively.

Table 11: Bus Result for MG System in Autonomous Mode after OPF

Bus no	V pu	Θ deg	P_G MW	Q_G MVar	P_L MW	Q_L MVar
1	1.047	0.353	82.43	-22.89	0	0
2	1.046	0.307	129.08	-42.89	0	0
3	1.045	-0.019	90.55	-69.33	50	10
4	1.049	-0.407	0.00	0.00	150	-55
5	1.05	-0.476	0.00	0.00	125	-85
6	1.045	0	23.54	-173.9	0	0
Total			325.6	-309.01	325	-130
Objective value = 5451.30 \$/hr						

Table 12: Results of flow in lines for MG System in Grid-Connected Mode after OPF

Line #	To Bus #	From Bus #	Line Flow, MVA	Max Flow, MVA
1	1	2	26.56	250
2	1	4	64.45	250
3	2	3	37.43	150
4	2	6	120.7	300
5	2	4	101.299	300
6	3	5	59.19	150
7	4	5	159.73	250
8	4	6	26.56	350

Table 13: Bus Result for MG System in Grid-Connected Mode after PF

Bus no	V (PU)	Θ (deg)	P_G (MW)	Q_G (MVAr)	P_L (MW)	Q_L (MVAr)	Objective Value
1	1.00	-3.430	50.00	-41.468	0	0	
2	1.00	-3.430	29.082	-18.053	0	0	
3	1.00	-3.773	90.550	-56.162	50	10	
4	1.004	-4.179	0.00	0.00	150	-55	
5	1.005	-4.258	0.00	0.00	125	-85	
6	1.00	0.00	159.949	-56.094	0	0	
Total			329.581	-171.77	325	-130	11724.67 $/hr

Table 14: Results of flow in lines for MG System in Grid-Connected Mode after PF

Line #	To Bus #	From Bus #	Line Flow, MVA	Max Flow, MVA
1	1	2	2.113	250
2	1	4	61.037	250
3	2	3	37.189	150
4	2	6	153.405	300
5	2	4	139.652	300
6	3	5	99.459	150
7	4	5	63.610	250
8	4	6	33.364	350

Table 15 gives the converter parameters for MG in connected mode before and after performing the power flow step to satisfy the power electronic constraints. As, it is shown from Table 15, the modulation index of the AC/DC/AC converter violates the desired value (1.0) before the optimization. But after optimization, the algorithm forced its value back to be 0.9928.

Table 15: Converter Parameters when MG Connected to Main Grid

Setting	**After OPF**	**After PF**
	Value (pu)	**Value (pu)**
A_{mi2}	1.3338	0.9928
A_{mo2}	0.8801	0.8536
α_{mi2}	30.9404	30.2971
α_{mo2}	-5.3645	-1.7269
A_{m3}	0.4504	0.4830
α_{m3}	13.9559	9.2352

5. Conclusion

This paper presents a new optimal operation algorithm of MG including DG units in autonomous and grid-connected mode. Based on the developed DG models, a two-steps optimal operation approach is presented. Step 1 of the approach solves for the AC network based on a conventional OPF method considering the regular OPF constraints of active power, reactive power, line flows, and bus voltage constraints while minimizing the fuel cost. However Step 2 utilizes terminal quantities of each DG, obtained from Step 1, and solves for the internal parameters/variables of the DG unit including those of the converter system and the prime source of the DG unit while making sure that the power electronic constraints are satisfied. If the power electronic constraints are not satisfied, so, step 3 has to be activated to force them even, if the optimal fuel cost has to be scarified. The approach provides an accurate and efficient optimal operation for a MG in the two modes of operation considering the power electronics constraints. The paper, also presents steady-state, fundamental-frequency models of two types of power electronic converters used for coupling DG units to the utility power grid. However, the proposed modeling approach can be conceptually expanded to other types of coupling converter systems. A Matlab program is developed to represent the proposed algorithm. The program is tested in various network conditions and verified by study cases in the two modes of operations (autonomous and non-autonomous). The results prove that the proposed algorithm is successfully forced the system to operate optimally at minimum fuel cost while satisfying all the specified constraints in the two modes of operation.

6. List of Symbols

P	Bus real power
Q	Bus reactive power
V_m	Amplitude bus RMS voltage
I	Bus RMS current
Fn	Network frequency
S_D	Load complex power
Q_c	Capacitor reactive power
P_g	Generator real power
Q_g	Generator reactive power
V_g	Generator RMS internal voltage
Θ_g	Generator voltage angle
w_g	Generator angular frequency
F_g	Generator output frequency
V_g	Instantaneous generator internal voltage
V_{mg}	Amplitude of generator internal voltage
I_g	Instantaneous generator current
V_i	Instantaneous converter input voltage
V_o	Instantaneous converter output voltage
V_{dc}	Converter DC-link voltage
R_g	Generator Resistance
L_g	Generator Reactance
R_f	Filter Resistance
L_f	Filter Reactance
A_{mi2}	Amplitude modulation index of inverter
A_{mo2}	Amplitude modulation index of rectifier
α_{mi2}	Inverter angle modulation index
α_{mo2}	Rectifier Inverter angle modulation index

A_{m3}	Amplitude modulation index of matrix converter
α_{m3}	Converter angle modulation index
MI	Modulation index of converter

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